

How Could CP -Invariance and Physics Beyond SM Be Tested in Polarized Proton Collisions at RHIC?

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Just in months ahead, the first high luminosity collisions of two polarized proton beams are expected to occur at RHIC in BNL at \sqrt{s} up to 500 GeV [1], bringing a new quality to the collider physics. In collisions of polarized particles, the presence of two axial vectors of initial polarizations, fully controlled by experimenters, may dramatically increase the number of available for tests correlations between participating vectors, generating asymmetries that could relatively easily be measured. In frame of Standard Model (SM), many of these asymmetries are either strongly suppressed or strictly prohibited. Therefore, if some of them were found nonzero, this could be an indication of a new physics beyond SM. If certain criteria met, it might be difficult to explain the observed nonzero correlations in theories without CP - and/or T -violation.

Key words: RHIC; Polarization; Spin-dependent asymmetries; Gauge bosons; Physics beyond SM; CP -violation.

Introduction

The expectations for a New Physics at the energy scale of hundreds of GeV are high. To some extent, the current status of SM is reminiscent to that of weak interactions in early 70th just before the discovery of J/ψ -meson and c -quark. At that time, something new had been expected to happen at the scale of a few GeV. Otherwise, the theories of weak interactions mediated by a vector W -boson could not survive because of their failure to explain the low

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$K_L^0 \rightarrow \mu^+ \mu^-$ decay rate [2]. Since 1977 [3], it is well understood that SM of electroweak interactions would experience quite serious complications if some new physics (Higgs? Compositeness? ...) does not show up at the energies below ~ 1 TeV. The energy range just above or even about W - and Z -masses is not excluded [4].

For 35 years since the discovery of CP -violation [5], many attempts have been undertaken to find more CP - and/or T -violating processes other than few known nonleptonic and semileptonic K^0 -decays. The negative results of these searches have found a quite natural explanation in frame of Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix phenomenology with a single nonzero phase that makes this matrix complex [6]. At present time, the CKM-matrix formalism is *de facto* the common language for SM interpretation of all already discovered CP -violating phenomena. At the currently achieved level of experimental and theoretical uncertainties, no clear contradictions had been found of the relations between few measured CP -odd parameters and the constraints of CKM-matrix.

A noticeably high “ CP -activity” has been quite evident for the last decade, and there is even more to come. Plans for CP -violation studies are in the research programs of all particle physics accelerator laboratories around the world, not mentioning B -factories proposed almost exclusively with the CP -violation in mind. Not undermining in any way the indisputable significance of the recent CP -activity, it should be underlined that its efforts are focused mainly on testing the CKM-based SM predictions for “direct” CP -violation in K^0 -decays as well as large CP -violation in b -quark transformations. Meanwhile, there is a quite widespread dissatisfaction and disbelief [7–13] that a single nonzero phase in CKM-matrix may be the only emergence of CP -violation in foreseeable energy range, and there are good reasons for such a discomfort. For example, various approaches to understanding the baryon asymmetry of the Universe require much stronger CP -violation than it is suggested in the minimal CKM-based SM [7]. In many models, CP -odd effects, sufficiently large for being detectable at high energy colliders, could be generated [7,8,12–14]. On the other hand, as it had been pointed out just a few years ago [13]: “*At present time published limits do not exist for the size of most CP -violating processes at 100 GeV scale. Thus heretofore undetected large ($\sim 50\%$) CP -violation could occur in some processes at high energy hadron colliders*”.

Since time of the first $p\bar{p}$ -collisions in the SPS, the energy scale of $\sim 10^2$ GeV is a common playground for experimenters. For the last decade, a number of papers have been published², exploring the feasibility to test CP - and T -invariance at large colliders in the modes other than B -decays. Most publications are focused on unpolarized colliders where the detection of CP - and/or

² See, for example, refs. [12–15].

T -violation requires to carry out quite difficult measurements of either fine balances between particle and antiparticle production in CP -conjugate processes, or polarizations³ of final jets to detect potentially nonzero T -odd correlations. Recently, some indications of the jet handedness correlations in Z^0 -decays, which were of the opposite sign to that expected in SM, had been reported [18]. The authors looked into the jet fragmentation mechanisms for a possible explanation. Alternatively, a presence of a tensor $q\bar{q}Z$ -coupling may also be responsible for the wrong sign correlations.

In the collisions of polarized particles, the number of potentially interesting T -odd as well as T -even correlations⁴ built from two axial⁵ and many polar⁶ vectors could be enormously large. A new physics and CP/T -violation mechanism behind these correlations could virtually be anywhere and everywhere [7–16]: in QCD quark-gluon and gluon-gluon coupling; in electroweak interactions mediated by the usual vector bosons as well as by suggested in some theories W' and Z' of higher masses; in Higgs sector; in the leptoquark exchange; due to spontaneous CP/T -violation; etc. However, an observation of a nonzero T -odd correlation may never be treated by itself as an evidence of T - or CP -violation because these correlations are easily generated by purely CP - and T -even initial and final state interactions. This is particularly serious issue at low momentum transfers, resulting in a very limited number of low energy processes being suitable to really test CP/T -invariance by measuring T -odd correlations [11,19–21]. At momentum transfers $\sim 10^4$ (GeV/c)² and more, the “spurious” asymmetries due to initial and final state interactions are expected to be small [12,13]. Nevertheless, even in high energy hard collisions, a comparison of asymmetries in CP -conjugate processes is still required for a conclusion on unambiguous and model independent observation of CP -violation, i.e. the same problem as in the measurements of balances between particle and antiparticle productions needs to be solved.

With all similarities, there is one important difference between comparisons of production cross sections and spin dependent asymmetries in CP -conjugate processes. In the case of cross sections, the CP -noninvariance of a detector may be the cause of false CP -odd-like effects due to unaccounted differences in detection efficiencies to particles and antiparticles⁷. In contrast, the measurement of spin dependent asymmetry in any particular process is usually not sensitive to uncertainties of the overall detection efficiency scale. Therefore, unaccounted differences of these scales in CP -conjugate processes do not introduce systematic errors to the asymmetry comparison. It is also worth

³ ...or handedness [17,18] ...

⁴ CP -violation may show up not only via T -odd asymmetries but also through purely T -even ones (see secs. 1 and 2 for examples).

⁵ Polarization vectors of projectiles.

⁶ Momenta of incident and final particles and jets in various processes.

⁷ See discussion in ref. [13].

noticing that, in the cases of small background (spurious) asymmetries, just “wrong” relative signs of detected asymmetries in CP -conjugate processes⁸ would be a sufficient evidence for CP -violation. And the last not the least, most reasonable models with CP -violation quite easily generate CP -odd spin dependent asymmetries, while measurements of cross section differences, averaged over initial and final polarizations, are often not sensitive to CP -violating amplitudes. The number of asymmetries to test would be particularly large if both transversely and longitudinally polarized projectiles were available.

Unlike in the accelerator experiments focused on decays of secondaries, the primary collisions and incident polarized particles themselves are parts of the reactions under investigation in the measurements of spin dependent asymmetries. Therefore, for having such experiments on CP -violation to be conclusive, an availability of CP -conjugate initial states is a must. From this point of view, $p\bar{p}$ -colliders with two polarized beams [22] would clearly be among the best and the most capable machines. In polarized $p\bar{p}$ collision, all variety of quark-antiquark, quark-gluon, and gluon-gluon interactions in CP -conjugate processes could be tested. Complimentary, polarized e^+e^- - and $\mu^+\mu^-$ -colliders could be used for studying CP/T -violation in the neutral current lepton scattering and annihilation, and at the energies above the threshold of W -pair production, the CP/T -invariance of charged current interactions could also be checked. Unfortunately, neither of these colliders with two polarized beams is currently available. Meanwhile, the CP -asymmetric collisions of two polarized proton beams are expected to be seen soon at RHIC in BNL [1], pursuing the goal to comprehensively explore the proton spin structure [23] as well as carry out a wide range study of parity violating phenomena in W^\pm - and Z^0 -boson productions and decays [24]. Although being obviously not the best for CP -invariance tests, collisions of two high energy polarized protons still have capabilities for, at minimum, scouting the problem in the processes with a reasonably clear picture of underlining parton interactions. At RHIC, the processes of hadronic leptonproduction via photon, W^\pm -, and Z^0 -boson exchange,

$$q\bar{q} \rightarrow W^\pm \rightarrow l\bar{l} \quad \text{and} \quad q\bar{q} \rightarrow Z^0/\gamma \rightarrow l^+l^-, \quad (1)$$

will probably be the cleanest ones to search for CP - and/or T -violation and other unusual and unexpected phenomena in.

In the rest of this paper, few examples of measurable asymmetries for processes (1) are shown⁹. These asymmetries, if found nonzero, could be an indication of a new physics beyond SM and, if certain criteria met, of a CP - and/or T -violation.

⁸ i.e. inconsistent with the CP -invariance; production cross sections could never be of “wrong” relative signs.

⁹ Some double-spin asymmetries had briefly been discussed earlier in reports [25].

1 Phenomenological model (example)

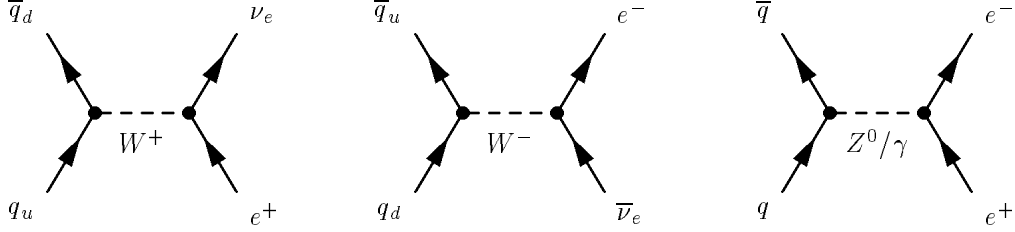


Fig. 1. The lowest order graphs for $q\bar{q} \rightarrow l\bar{l}$ (e^+/e^- and $\nu_e/\bar{\nu}_e$ are shown here for leptons).

In the lowest order, processes (1) are represented by the s -channel annihilation graphs shown in Fig. 1. Unusual interactions, including CP - and/or T -violation, may be present in either or both of two vertices. To be specific, the further discussion is held in frame of one phenomenological modification of SM's electroweak coupling which had earlier been used elsewhere [12]. In this model, an effective Lagrangian of charged current $q_u q_d W$ -interactions is:

$$L_c = \frac{g}{2\sqrt{2}} \left\{ [W_\mu^- \bar{q}_d \gamma^\mu (f_V^+ + f_V^- \gamma_5) q_u + W_\mu^+ \bar{q}_u \gamma^\mu (f_V^{*+} + f_V^{*-} \gamma_5) q_d] + \right. \\ \left. + \frac{1}{\Lambda_q} [\partial_\nu W_\mu^- \bar{q}_d \sigma^{\mu\nu} (f_T^+ + f_T^- \gamma_5) q_u + \partial_\nu W_\mu^+ \bar{q}_u \sigma^{\mu\nu} (f_T^{*+} - f_T^{*-} \gamma_5) q_d] \right\} \quad (2)$$

where g is a coupling constant, presumably on the order of the electroweak one, Λ_q is the energy scale of the “full strength” tensor¹⁰ interactions, and the asterisk denotes the complex conjugate. The notations q_u and q_d are for the “upper” (u and c)¹¹ and “lower” (d, s, b) quarks respectively. The usual ($V-A$) interactions correspond to $f_V^+ = f_V^- = 1$ with f_T^\pm equal to zero¹². The CP - and T -invariance of model (2) is broken if any or all “formfactors” $f_{V,T}^\pm$ were complex. In the neutral current effective Lagrangian of type (2) for $q\bar{q}Z$ -interactions¹³, three formfactors, f_V^\pm and f_T^+ , must be real. CP -violation may occur due to only tensor coupling with a purely imaginary $f_T^- \neq 0$. In the calculations below, the effective Lagrangians of type (2) with changed notations: $f_{V,T}^\pm \rightarrow l_{V,T}^\pm$ and $\Lambda_q \rightarrow \Lambda_l$, have also been used to describe the lepton coupling to W - and Z -bosons. In this phenomenological and rather illustrative example, we do not speculate on the nature of underlining fundamental interactions which may potentially induce nonstandard terms and CP -odd phases

¹⁰ The shortcuts “vector” and “tensor” are used for couplings without and with derivatives ∂_ν , respectively.

¹¹ t -quark is virtually not reachable at RHIC.

¹² In this paper: $\gamma_5 = -i\gamma^0\gamma^1\gamma^2\gamma^3$ and $\sigma^{\mu\nu} = \frac{1}{2}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)$.

¹³ ... of a truly neutral $q\bar{q}$ -pair, consisting of a fermion q and its antiparticle.

in Lagrangian (2). We do not speculate on the expected magnitudes for these terms either. We just mention here that the currently available experimental data from the low energy searches for a weak tensor coupling generally do not exclude f_T^\pm and/or $l_T^\pm \sim 1$ for $\Lambda_{q,l} \geq 10^2$ GeV [26].

In model (2), the tree-level cross section for charged current annihilation (1) of polarized quark and antiquark could be written as:

$$\frac{d\hat{\sigma}}{d\Omega} \simeq \frac{g^4 \hat{s} \{ |M_{fi}^{VV}|^2 + \frac{\sqrt{\hat{s}}}{\Lambda_q} |M_{fi}^{VT}|^2 + \frac{\hat{s}}{\Lambda_q^2} |T_{fi}^{TT}|^2 \}}{64 \{ (\hat{s} - M_W^2)^2 + \hat{s}^2 \Gamma_W^2 / M_W^2 \}} \quad (3)$$

where M_W and Γ_W are for the W -boson mass and width, respectively; $\sqrt{\hat{s}}$ is the total center-of-mass (c.m.) energy of colliding quark and antiquark; $|M_{fi}^{VV}|^2$ represents the contribution of $q\bar{q}W$ vector coupling; $|M_{fi}^{TT}|^2$ is due to $q\bar{q}W$ tensor coupling; and $|M_{fi}^{VT}|^2$ is for the interference between vector and tensor. Using the standard technique, the following formulae for $|M_{fi}|^2$, summed over final lepton polarizations, could be obtained in the c.m. frame of colliding quark and antiquark¹⁴:

$$\begin{aligned} |M_{fi}^{VV}|^2 = & \frac{1}{16} \left\{ |f_V^+ + f_V^-|^2 \cdot |l_V^+ + l_V^-|^2 (1 - \lambda_q)(1 + \lambda_{\bar{q}}) + \right. \\ & \left. + |f_V^+ - f_V^-|^2 \cdot |l_V^+ - l_V^-|^2 (1 + \lambda_q)(1 - \lambda_{\bar{q}}) \right\} \times \left\{ 1 + \mathbf{n}_p \cdot \mathbf{n}_k \right\}^2 + \\ & + \frac{1}{16} \left\{ |f_V^+ + f_V^-|^2 \cdot |l_V^+ - l_V^-|^2 (1 - \lambda_q)(1 + \lambda_{\bar{q}}) + \right. \\ & \left. + |f_V^+ - f_V^-|^2 \cdot |l_V^+ + l_V^-|^2 (1 + \lambda_q)(1 - \lambda_{\bar{q}}) \right\} \times \left\{ 1 - \mathbf{n}_p \cdot \mathbf{n}_k \right\}^2 + \\ & + \frac{\hat{s}}{8\Lambda_l} \left\{ |f_V^+ + f_V^-|^2 (1 - \lambda_q)(1 + \lambda_{\bar{q}}) + |f_V^+ - f_V^-|^2 (1 + \lambda_q)(1 - \lambda_{\bar{q}}) \right\} \times \\ & \times \left\{ |l_T^+|^2 + |l_T^-|^2 \right\} \times \left\{ 1 - (\mathbf{n}_p \cdot \mathbf{n}_k)^2 \right\} + \end{aligned} \quad (4.1)$$

$$\begin{aligned} & + \frac{1}{2} \left\{ (|l_V^+|^2 + |l_V^-|^2) - \frac{\hat{s}}{\Lambda_l^2} (|l_T^+|^2 + |l_T^-|^2) \right\} \times \left\{ (|f_V^+|^2 - |f_V^-|^2) \times \right. \\ & \times \{ (\boldsymbol{\zeta}_q^\perp \cdot \mathbf{n}_k)(\boldsymbol{\zeta}_{\bar{q}}^\perp \cdot \mathbf{n}_k) - \frac{1}{2}(\boldsymbol{\zeta}_q^\perp \cdot \boldsymbol{\zeta}_{\bar{q}}^\perp)[1 - (\mathbf{n}_p \cdot \mathbf{n}_k)^2] \} \pm \end{aligned} \quad (4.2)$$

$$\begin{aligned} & \pm \text{Im}(f_V^+ f_V^{*-}) \times \\ & \times \{ (\mathbf{n}_k \cdot [\boldsymbol{\zeta}_q^\perp \times \mathbf{n}_p])(\boldsymbol{\zeta}_{\bar{q}}^\perp \cdot \mathbf{n}_k) + (\mathbf{n}_k \cdot [\boldsymbol{\zeta}_{\bar{q}}^\perp \times \mathbf{n}_p])(\boldsymbol{\zeta}_q^\perp \cdot \mathbf{n}_k) \} \} \quad (4.3) \end{aligned}$$

$$|M_{fi}^{TT}|^2 = \frac{1}{8} \left\{ (|l_V^+|^2 + |l_V^-|^2)[1 - (\mathbf{n}_p \cdot \mathbf{n}_k)^2] + \frac{\hat{s}}{\Lambda_l^2} (|l_T^+|^2 + |l_T^-|^2)(\mathbf{n}_p \cdot \mathbf{n}_k)^2 \right\} \times$$

¹⁴ There are no doubts that various pieces of these formulae were published and known since, probably, 60th–70th and some even earlier.

$$\times \left\{ |f_T^+ \pm f_T^-|^2 (1 - \lambda_q)(1 - \lambda_{\bar{q}}) + |f_T^+ \mp f_T^-|^2 (1 + \lambda_q)(1 + \lambda_{\bar{q}}) + \right. \quad (5.1)$$

$$\left. + 2(|f_T^+|^2 - |f_T^-|^2)(\zeta_q^\perp \cdot \zeta_{\bar{q}}^\perp) - 4 \text{Im}(f_T^+ f_T^{*-}) (\mathbf{n}_p \cdot [\zeta_q^\perp \times \zeta_{\bar{q}}^\perp]) \right\} \quad (5.2)$$

$$\begin{aligned} |M_{fi}^{VT}|^2 = & \frac{1}{2} \left\{ (|l_V^+|^2 + |l_V^-|^2) - \frac{\hat{s}}{\Lambda_l^2} (|l_T^+|^2 + |l_T^-|^2) \right\} \times (\mathbf{n}_k \cdot \mathbf{n}_p) \times \\ & \times \left\{ \text{Re}[(f_V^+ f_T^{*-} \mp f_V^- f_T^{*-}) + \lambda_{\bar{q}}(\mp f_V^+ f_T^{*-} + f_V^- f_T^{*-})](\mathbf{n}_k \cdot [\zeta_q^\perp \times \mathbf{n}_p]) - \right. \\ & - \text{Im}[(f_V^+ f_T^{*-} \mp f_V^- f_T^{*-}) + \lambda_{\bar{q}}(\mp f_V^+ f_T^{*-} + f_V^- f_T^{*-})](\zeta_q^\perp \cdot \mathbf{n}_k) + \\ & + \text{Re}[(f_V^+ f_T^{*+} \pm f_V^- f_T^{*+}) - \lambda_q(\pm f_V^+ f_T^{*+} + f_V^- f_T^{*+})](\mathbf{n}_k \cdot [\zeta_{\bar{q}}^\perp \times \mathbf{n}_p]) + \\ & + \text{Im}[(f_V^+ f_T^{*+} \pm f_V^- f_T^{*+}) - \lambda_q(\pm f_V^+ f_T^{*+} + f_V^- f_T^{*+})](\zeta_{\bar{q}}^\perp \cdot \mathbf{n}_k) \Big\} + \\ & + \text{Re}(l_V^+ l_V^{*-}) \times \\ & \times \left\{ \text{Re}[(\mp f_V^+ f_T^{*-} + f_V^- f_T^{*-}) + \lambda_{\bar{q}}(f_V^+ f_T^{*-} \mp f_V^- f_T^{*-})](\mathbf{n}_k \cdot [\zeta_q^\perp \times \mathbf{n}_p]) - \right. \\ & - \text{Im}[(\mp f_V^+ f_T^{*-} + f_V^- f_T^{*-}) + \lambda_{\bar{q}}(f_V^+ f_T^{*-} \mp f_V^- f_T^{*-})](\zeta_q^\perp \cdot \mathbf{n}_k) + \\ & + \text{Re}[(\pm f_V^+ f_T^{*+} + f_V^- f_T^{*+}) - \lambda_q(f_V^+ f_T^{*+} \pm f_V^- f_T^{*+})](\mathbf{n}_k \cdot [\zeta_{\bar{q}}^\perp \times \mathbf{n}_p]) + \\ & + \text{Im}[(\pm f_V^+ f_T^{*+} + f_V^- f_T^{*+}) - \lambda_q(f_V^+ f_T^{*+} \pm f_V^- f_T^{*+})](\zeta_{\bar{q}}^\perp \cdot \mathbf{n}_k) \Big\} \quad (6) \end{aligned}$$

In the formulae above, $\mathbf{n}_p = \mathbf{p}/|\mathbf{p}|$ and $\mathbf{n}_k = \mathbf{k}/|\mathbf{k}|$ where $\mathbf{p} \equiv \mathbf{p}_q$ is the momentum of the incident quark and $\mathbf{k} \equiv \mathbf{k}_{e^-}$ or $\mathbf{k} \equiv \mathbf{k}_\nu$ is the momentum of the final lepton; $\lambda_q = (\zeta_q \cdot \mathbf{p}_q)/|\mathbf{p}_q|$ and $\lambda_{\bar{q}} = (\zeta_{\bar{q}} \cdot \mathbf{p}_{\bar{q}})/|\mathbf{p}_{\bar{q}}|$ are for helicities, and ζ_q^\perp and $\zeta_{\bar{q}}^\perp$ for transverse polarizations of the incident quark and antiquark, respectively. Only the main contributions to the cross section were kept in eqs. (4)–(6), neglecting all others suppressed by powers of $m_{q,l}/\sqrt{\hat{s}}$, where $m_{q,l}$ is for the masses of participated in the reaction quarks and leptons. The upper and lower signs correspond to W^+ and W^- productions, respectively¹⁵.

2 Discussion

As one can see from eqs. (3)–(6), new physics in the processes (1) at polarized hadron colliders may show up via a number of measurable characteristics.

The deviation of the $q\bar{q}W$ -coupling from the standard $(V-A)$ form¹⁶ affects

¹⁵ For a neutral current process, the result does not depend on these signs due to restrictions on allowed choices for $f_{V,T}^\pm$.

¹⁶ ...or from the usual SM's mixture of V and A in the neutral current $q\bar{q}Z/\gamma$ -coupling.

the lepton production distributions in polar angle $\theta = \widehat{\mathbf{k} \mathbf{p}}$. However, this could hardly be exploited for new physics searches at hadron colliders because θ -distributions are also products of not so well known parton structure functions. In the real life, the measurements of lepton spectra and θ -distributions are rather used to reconstruct structure functions, assuming the known interactions at the parton level.

The same is true for dependences (4.1) and (5.1) of the production cross sections on quark helicities. To reconstruct these dependences back to the quark-parton level, using experimental data from hadron collisions, the knowledge of the spin-dependent parton structure functions is required. In the real life, again, the situation is quite opposite: the measurements of these structure functions themselves will be the main focus of the RHIC experimental program with polarized protons. At the tree-level of the model in consideration, neither θ -distributions nor helicity dependences of cross sections are sensitive to the CP -violating phases in Lagrangian (2), although this does not mean that such a sensitivity may not be present in others, more sophisticated theories.

The situation with asymmetries (4.2), (4.3), (5.2), and (6) in collisions of transversely polarized nucleons is quite different. In SM, most transverse asymmetries are either strongly suppressed or strictly prohibited. Therefore, if some of them were found to be sufficiently large, this would be an indication of deviations from SM, regardless of the spin structure of colliding hadrons.

The first example is the well known P - and T -even double-spin azimuthal anisotropy (4.2) of lepton production:

$$A_{TT} \propto (|f_V^+|^2 - |f_V^-|^2) \cdot |\zeta_q^\perp| \cdot |\zeta_{\bar{q}}^\perp| \cdot \cos(\varphi_{\bar{q}q} - 2\varphi_{kq}), \quad (7)$$

where $\varphi_{\bar{q}q} = \widehat{\zeta_{\bar{q}}^\perp \zeta_q^\perp}$ and $\varphi_{kq} = \widehat{\mathbf{k}_\perp \zeta_q^\perp}$ with $\mathbf{k}_\perp = \mathbf{k} - (\mathbf{k} \cdot \mathbf{n}_p)\mathbf{n}_p$. The tree-level $A_{TT} = 0$ in charged current ($V-A$)-interactions. However, A_{TT} is expected to be measurably large in the neutral current Drell-Yan process, $q\bar{q} \rightarrow Z^0/\gamma \rightarrow l^+l^-$, making it attractive for measurements of the quark transversity distributions $h_1(x)$ in proton [27–29].

The double-spin T -odd asymmetry (4.3) due to CP -violation in the $q\bar{q}W$ vector coupling looks similar to A_{TT} , but rotated by 45° :

$$A_{TT}^\perp \propto \pm \text{Im}(f_V^+ f_V^{*-}) \cdot |\zeta_q^\perp| \cdot |\zeta_{\bar{q}}^\perp| \cdot \sin(\varphi_{\bar{q}q} - 2\varphi_{kq}). \quad (8)$$

In model (2), this asymmetry is the “true” CP -odd one and, because of that, it is of the opposite signs in two CP -conjugate processes of W^\pm -production. A “spurious” CP -even A_{TT}^\perp would not change sign under CP -conjugation. If A_{TT}^\perp anisotropy would have ever been detected in a neutral current annihilation¹³,

it could never be a true CP -odd but only a spurious CP -even one due to some CP -conserving initial and/or final state interactions.

Without an interference to the vector, the tensor coupling of transversely polarized quarks to gauge bosons does not generate azimuthal anisotropies of lepton production at the tree level. However, it may generate cross section dependences (5.2) on the relative orientation of vectors ζ_q^\perp and $\zeta_{\bar{q}}^\perp$. The CP -even cross section difference $\Delta\sigma_N \propto (|f_T^+|^2 - |f_T^-|^2)(\zeta_q^\perp \cdot \zeta_{\bar{q}}^\perp)$ would be nonzero if $|f_T^+| \neq |f_T^-|$. CP -violation in the tensor coupling makes cross sections dependent on also the T -odd product $(\mathbf{n}_p \cdot [\zeta_q^\perp \times \zeta_{\bar{q}}^\perp])$ with the measurable $\Delta\sigma_\perp = \sigma_\perp^R - \sigma_\perp^L \propto \text{Im}(f_T^+ f_T^{*-}) (\mathbf{n}_p \cdot [\zeta_q^\perp \times \zeta_{\bar{q}}^\perp])$, where cross sections $\sigma_\perp^{R,L}$ are for the “right”- and “left”-handed orientations of vectors ζ_q^\perp , $\zeta_{\bar{q}}^\perp$, and \mathbf{n}_p , respectively. In formula (5.2), the true CP -odd $\Delta\sigma_\perp$ is of the same sign in W^{+-} and W^- -productions, but a spurious CP -even $\Delta\sigma_\perp$ must change its sign under CP -conjugation. In a neutral current annihilation, neither CP -conserving interactions could generate a nonzero $\Delta\sigma_\perp$. Therefore, an observation of $\Delta\sigma_\perp \neq 0$ in a neutral-current quark (or lepton) and its antiparticle annihilation would be an unambiguous evidence of CP -violation. With all attractiveness, the reliable measurements of $\Delta\sigma_{N,\perp}$ should be expected to be significantly more difficult compared to azimuthal anisotropies. The reason is the high sensitivity of $\Delta\sigma_{N,\perp}$ measurements to spin misalignments, namely, to unaccounted longitudinal components of the colliding beam polarizations.

The single-spin and double-spin¹⁷ asymmetries of type (6), arising from the vector-tensor interference, are strongly suppressed at the SM’s tree level. Both, T -even and T -odd asymmetries may potentially be generated. As usually, to determine, whether CP -violation takes place, the relative signs of detected asymmetries in CP -conjugate processes must be compared. It is interesting to notice that, in eq. (6), the CP -odd imaginary parts are before T -even correlations $(\zeta^\perp \cdot \mathbf{n}_k)$, while the CP -even real parts of participating formfactors $f_{V,T}^\pm$ stand before T -odd products of three vectors, $(\mathbf{n}_k \cdot [\zeta^\perp \times \mathbf{n}_p])$. This, to some extent surprising result, is apparently the feature of the particular model in consideration, although it is probably not so difficult to invent other models where CP -violation could generate T -odd single- and double-spin asymmetries of type (6) as well.

Imaginary parts of formfactors $l_{V,T}^\pm$ are not present in formulae (4)–(6) at all. This means that, without tracking the polarizations of final leptons, processes (1) are not sensitive to CP/T -violation in the lepton sector.

At the early stage of just “hunting” for unusual correlations at polarized hadron colliders, it is probably not necessary to know much about the spin-dependent parton structure functions of colliding hadrons. However, to dis-

¹⁷ ... with one quark transversely and the other one longitudinally polarized ...

tinguish CP -odd and CP -even correlations by comparing asymmetries in CP -conjugate processes, at least the relative signs of polarizations and often the directions of motions of the primary hardly collided quark and antiquark need to be known. This means that it would be necessary, at minimum, to identify with a reasonably high certainty the parent projectiles of incident quark and antiquark in every single event of W^\pm - and/or Z^0 -production. Then, some knowledges about h_1^q and $h_1^{\bar{q}}$ obtained from, for example, A_{TT} measurements in Drell-Yan process could be used to determine the relative q and \bar{q} polarization signs.

The identification of the predominant parent projectiles for q and \bar{q} would be quite obvious at $p\bar{p}$ -colliders. At proton-proton colliders, where the situation is not the same clear, the properties of gauge boson production kinematics may help. In pp -collisions, gauge bosons will mostly be produced in hard processes, involving a valence quark from one proton and sea antiquark from the other proton. From multiple simulations it follows that gauge bosons will likely be moving in the direction of the incident “hard” valence quark rather than in the direction of a “soft” sea antiquark [30]. This means that, if the polarization of one beam was altered, the effects detected in the forward and backward hemispheres in respect to the direction of this particular beam would have the different origins. In the forward direction, effects would mainly be due to changed polarizations of valence quarks. But in the backward hemisphere, effects would likely be caused by the alteration of polarizations of sea antiquarks. The production kinematics of Z -bosons will fully be reconstructed in every single event of type (1) as a part of the Z^0 -decay identification procedure. In the case of W^\pm , the situation is more difficult because of the neutrino escape. However, according to simulations [30], the W ’s kinematics could also be determined with some certainty which would probably be sufficient to separate W -bosons, emerging into the forward and backward hemispheres.

What might be the expectations for magnitudes of the nonstandard asymmetries discussed above in polarized proton collisions at RHIC? To answer this question, two other questions should be addressed first. In general, question number one is about the predictions of various theoretical models for the types and sizes of spin dependent correlations at the quark-parton level. Speaking in narrower terms of Lagrangian (2), it is about predictions for the formfactors $f_{V,T}^\pm$ and $l_{V,T}^\pm$ and their CP -violating phases, as well as for the tensor interactions’ energy scales $\Lambda_{q,l}$. We will not discuss these issues here, leaving them for the expertise of theorists, along with the analysis of restrictions to parameters of theoretical models, arising from the available experimental data. The estimations for background asymmetries due to higher orders SM interactions could also be a natural part of this expertise.

Question number two, on how to transfer spin correlations at the quark-parton level to the asymmetries in proton collisions and back, is expected to be ad-

dressed by simulations in the nearest future. Here, just some crude estimates for CP -odd asymmetries of model (2), derived from the A_{TT} -study of ref. [29], are provided. In that study, the upper limits for the A_{TT} -asymmetry at RHIC have been obtained, using the assumption on saturation of Soffer's inequality [28] for the parton transversity distributions in proton. It had been shown that, for high mass Drell-Yan pairs, the A_{TT} -asymmetry in pp -collisions at RHIC could be as large as 3–5%. The comparison of the A_{TT} -term to terms for the other double-spin asymmetries in eqs. (4)–(6) gives that all CP -odd double-spin asymmetries should be expected in the same scale of $\sim(0.03\text{--}0.05)$ but multiplied, of course, by the factors $\text{Im}(F_1 F_2^*)$ where $F_{1,2}$ are for either f_V^\pm or $f_T^\pm \times M_W/\Lambda_q$, depending on the particular asymmetry in consideration. The similar exercise leads to the estimate for single-spin asymmetries at $\sim \sqrt{0.03\text{--}0.05} \times \text{Im}(f_V f_T^*) \times M_W/\Lambda_q \sim (0.1\text{--}0.3) \times \text{Im}(f_V f_T^*) \times M_W/\Lambda_q$.

With the statistics accumulation $\sim(3\text{--}4)\cdot 10^3$ of Z -boson's and $\sim 10^4\text{--}10^5$ of W 's lepton decays a year [31], RHIC's sensitivity to the spin asymmetries in processes (1) is expected to be $\sim 10^{-2}$ at pp -level. This makes measurements of the discussed here double-spin correlations just marginally sensitive to even large deviations from SM in quark-parton interactions. However, a sizeable presence of, for example, CP -even and/or CP -odd tensor interactions should be detectable at RHIC through the measurements of single-spin transverse asymmetries.

3 Conclusion

In this paper, some measurable spin correlations, which may signal about New Physics beyond SM at RHIC with polarized protons, have been highlighted. A comparison of these correlation in what is believed CP -conjugate processes at the quark-parton interaction level may provide indications of large CP - and/or T -violation at the energy scale of $\sim 10^2$ GeV. To make it clear, an absolutely unambiguous and model independent evidence of a CP -violation could probably never be obtained from the measurements of spin-dependent production asymmetries at pp -colliders. However, strong enough indications may potentially emerge if, for example, several asymmetries have been detected in the same process and, with either assumption about the spin structure of proton, one part of these asymmetries behaved as a CP -even under CP -conjugation, and the other part as a CP -odd, and vice versa. In the situations like this, it might probably not be so easy to reconcile CP -conservation with the current quark-parton picture of gauge boson hadroproduction.

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